Forward Physics Facility and High Energy Neutrinos

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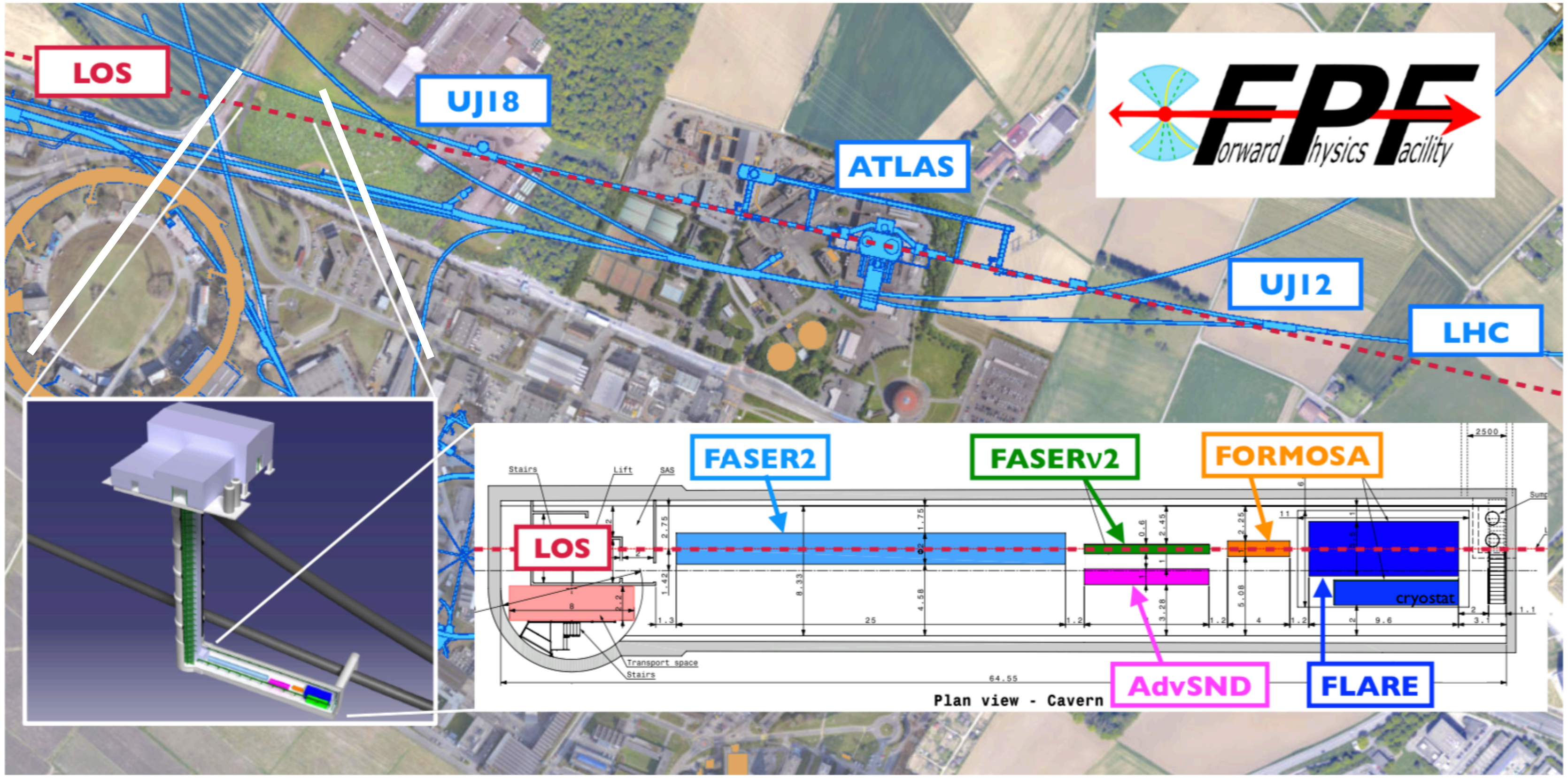
FPF White Papers: arXiv:2203.05090 (“long paper”) and Anchordoqui et al. Phys. Rept. 968 (2022) 1 (“short paper”)

The Forward Physics Facility

The Forward Physics Facility (FPF) is a proposal to create a cavern with the space and infrastructure to support a suite of far-forward experiments at the Large Hadron Collider during the High Luminosity era.

FPF experiments will detect about 1M neutrino interactions (1K tau neutrinos) with neutrino energies up to a few TeV



Need the facility infrastructure and detectors designed for Standard Model and BSM Physics.

FPF White Papers: arXiv:2203.05090 (“long paper”), see also Anchordoqui et al. Phys. Rept. 968 (2022) 1

Forward rapidity regions for detectors:

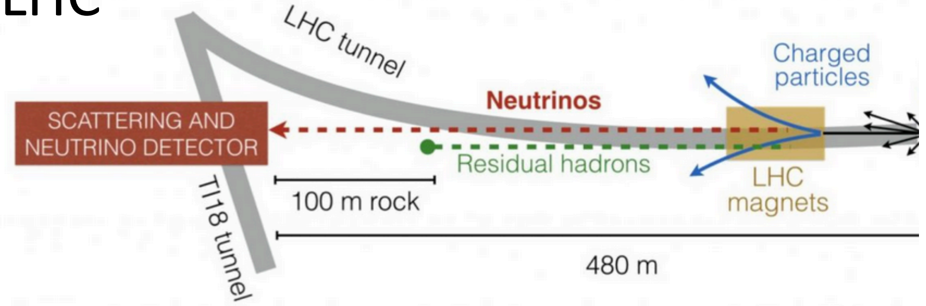
Detector			
Name	Mass	Coverage	Luminosity
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}

Run 3

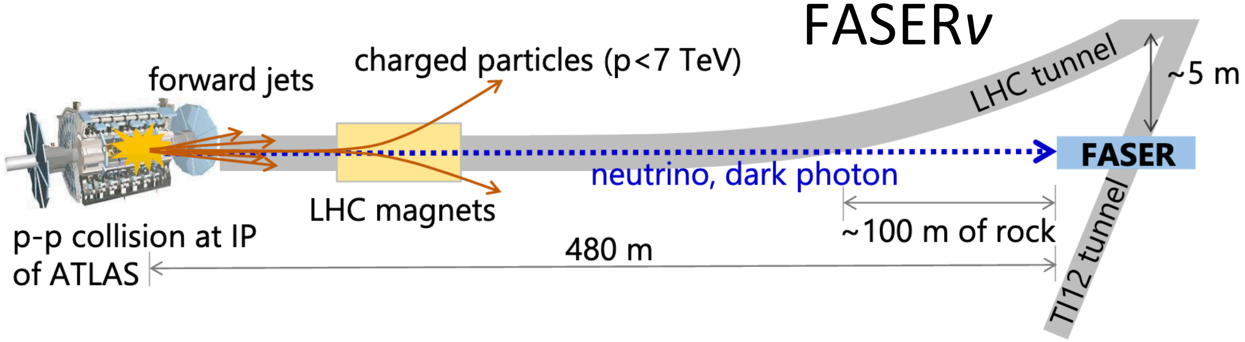
FASERν and SND@LHC detectors are installed

AdvSND (“near”) in range $4<\eta<5$

SND@LHC



FASERν



The Physics at FPF

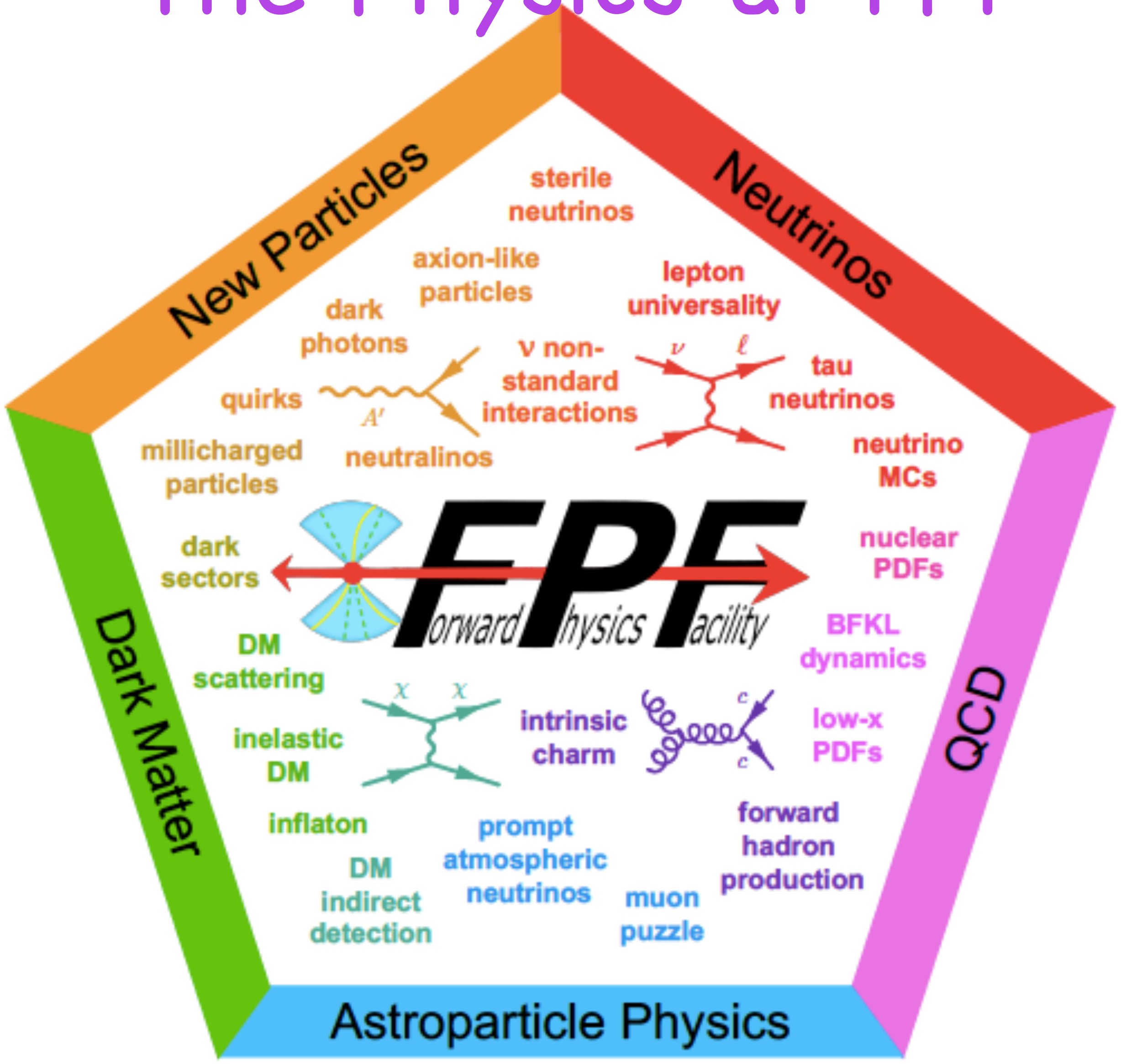


Figure 2: The Forward Physics Facility will probe topics that span multiple frontiers, including new particles, neutrinos, dark matter, QCD, and astroparticle physics.

Production of Neutrinos

At LHC (forward detectors: FASERnu ...):

p + p → pions, kaons, D-mesons .. → neutrinos

Energy of protons 14TeV (LHC beam)

Atmospheric neutrinos:

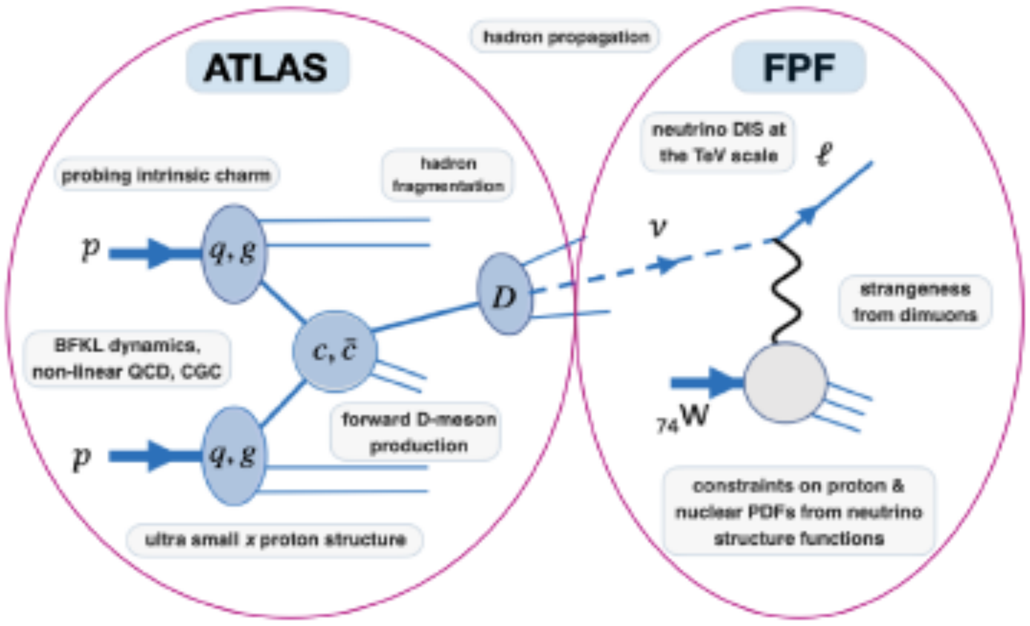
p + Air (p) → pions, kaon, D-mesons →neutrinos

Folding comic ray proton spectrum with the production

Astrophysical neutrinos (from AGNs, GRB..)

p + p and p+ gamma, folding with the proton energy spectrum

QCD (neutrino production)



Forward neutrino production is a probe of forward hadron production, BFKL dynamics, PDFs at ultra small x (10^-7) and small Q^2

Important implications for high energy neutrino experiments

Charm Production in NLO pQCD using PDFs

The total charm cross section in pQCD is given by:

$$\sigma(pp \rightarrow c\bar{c}X) = \int dx_1 dx_2 G(x_1, \mu^2) G(x_2, \mu^2) \hat{\sigma}_{gg \rightarrow c\bar{c}}(x_1 x_2 s)$$

and differential charm cross section

$$\frac{d\sigma}{dx_F} = \int \frac{dM^2_{c\bar{c}}}{(x_1 + x_2)s} \sigma_{gg \rightarrow c\bar{c}}(\hat{s}) G(x_1, \mu^2) G(x_2, \mu^2)$$

where

$x_1,\ x_2:$

$$x_F = x_1 - x_2$$

$$x_F \simeq x_E = E/E'$$

$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}}{s}} \pm x_F\right)$$

$$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1$$

$$E \sim 10^7 \text{ GeV} \rightarrow x_2 \sim 10^{-6}$$

$$x_{1,2} \sim m_c/2m_p E_\nu$$

For high energies we need gluon PDF for small x, and low Q^2

FONLL program: Cacciari, Greco and Nason, JHEP 05 (1998) 007; Cacciari, Frixione, Nason, JHEP 03 (2001) 006

Calculated in pQCD by matching the Fixed Order NLO terms with NLL high p_T resummation

Charm Production in k_T Factorization Approach

$$\frac{d\sigma}{dx_F}(s, m_Q^2) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} dz \delta(zx_1 - x_F) x_1 g(x_1, M_F) \int \frac{dk_T^2}{k_T^2} \hat{\sigma}^{\text{off}}(z, \hat{s}, k_T) f(x_2, k_T^2)$$

In the above formula, x_F is the Feynman variable for the produced heavy quark, $x_1 g(x_1, M_F)$ is the integrated gluon density on the projectile side, $\hat{\sigma}^{\text{off}}(z, \hat{s}, k_T)$ is the partonic cross section for the process $gg^* \to Q\bar{Q}$, where g^* is the off-shell gluon on the target side, and $f(x_2, k_T^2)$ is the unintegrated gluon density. For the unintegrated gluon density, we have used the resummed version of the BFKL evolution which includes important subleading effects due to DGLAP evolution and the kinematical constraint

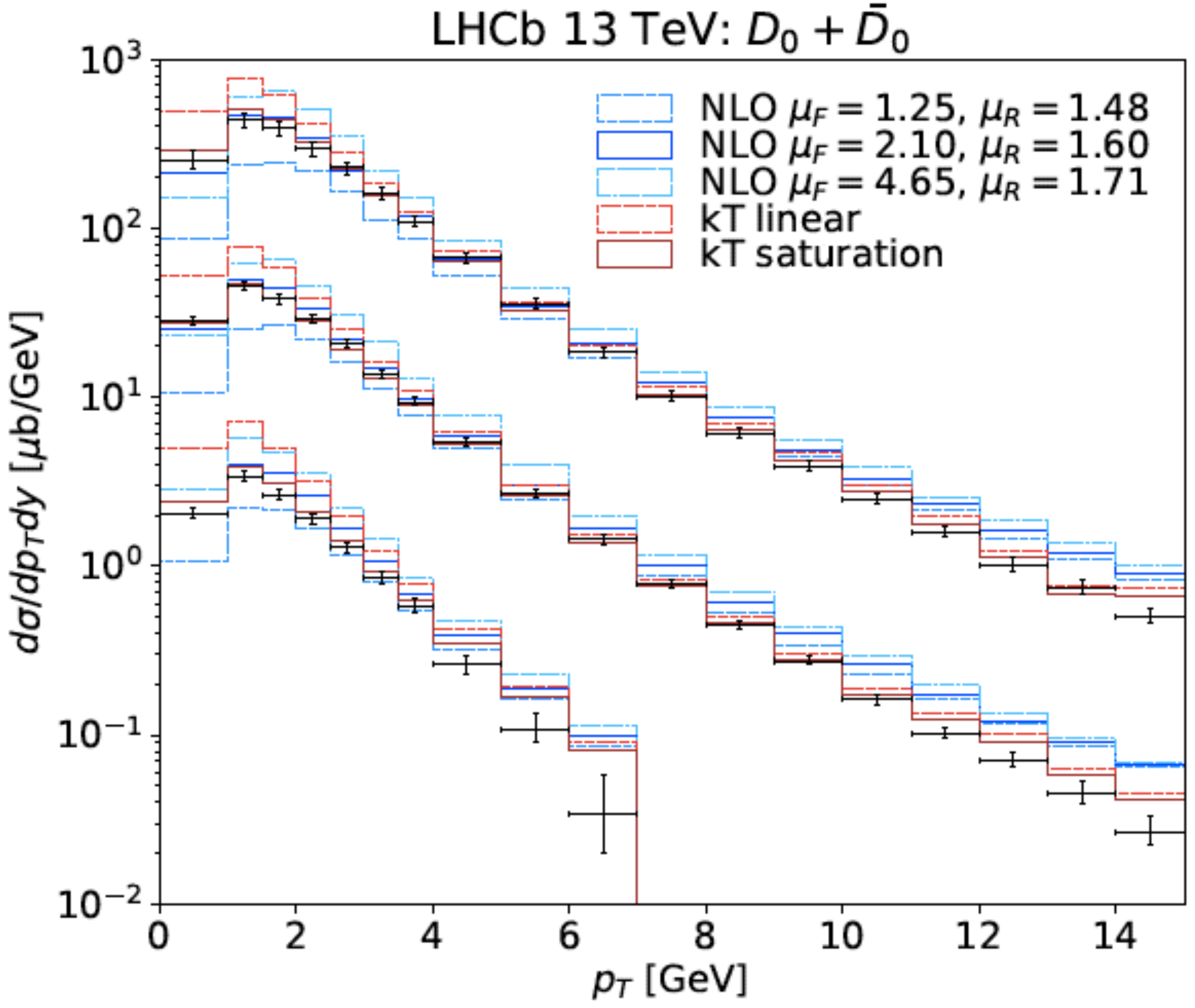
Theoretical uncertainties

Parton distribution functions at small x and small Q^2 (mostly gluons, unconstrained by HERA data), Factorization and Renomalization scale, charm quark mass, Fragmentation function

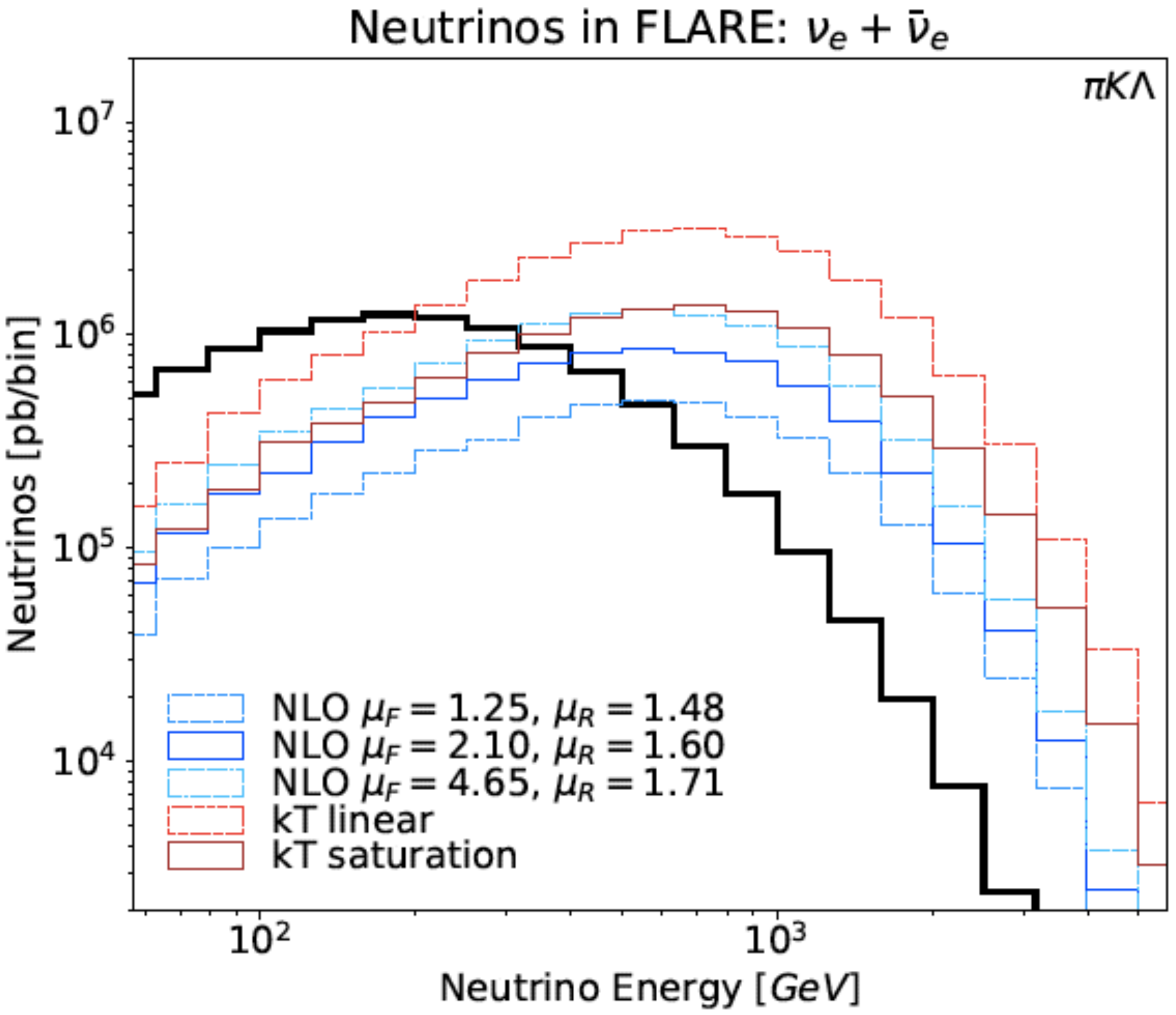
We use LHCb and ALICE data in different rapidity regions and at several energies to reduce theoretical uncertainties (LHCb data covers rapidity up to 4.5)

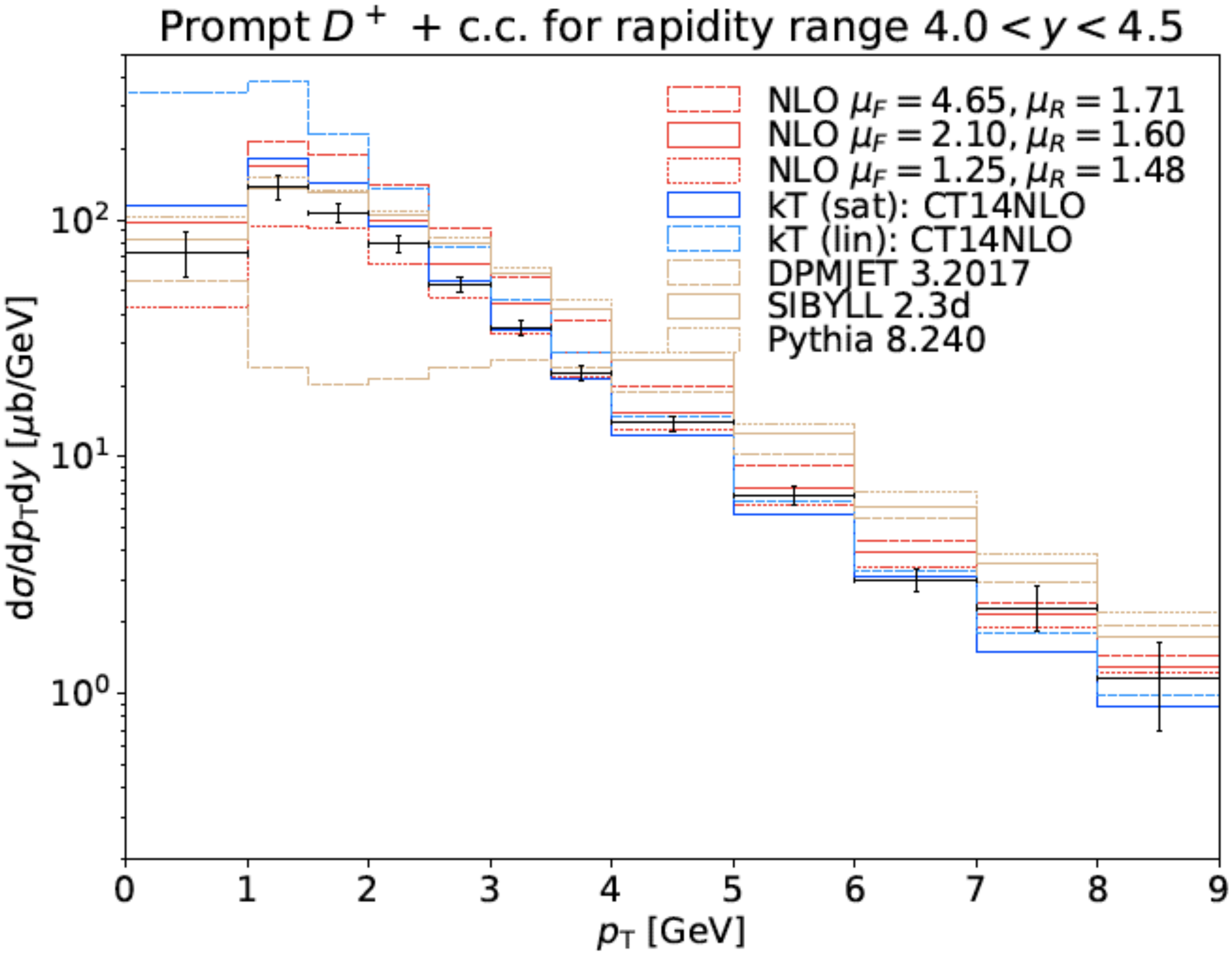
k_T factorization approach depends on gluon distribution at large-x, charm quark mass

D-meson production at LHCb in different rapidity regions



Neutrinos from D-meson decays

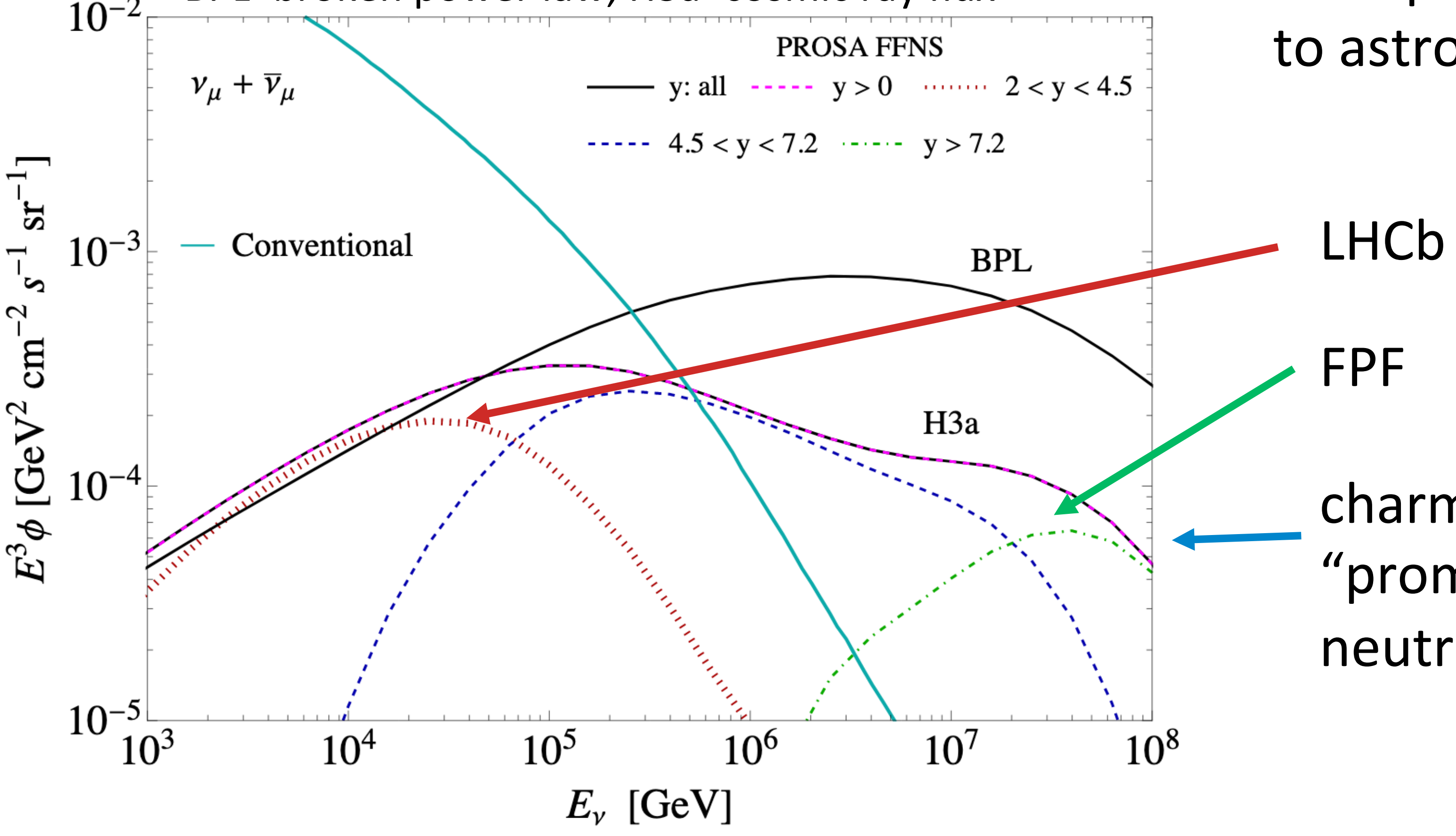




Prompt D^+ + c.c. for rapidity range $4.0 < y < 4.5$
NLO $\mu_F = 4.65, \mu_R = 1.71$
NLO $\mu_F = 2.10, \mu_R = 1.60$
NLO $\mu_F = 1.25, \mu_R = 1.48$
kT (sat): CT14NLO
kT (lin): CT14NLO
DPMJET 3.2017
SIBYLL 2.3d
Pythia 8.240
$d\sigma/dp_T dy$ [μb/GeV]
10^2
10^1
10^0
0
1
2
3
4
5
6
7
8
9
p_T [GeV]

Astroparticle physics connections – prompt atmospheric neutrinos

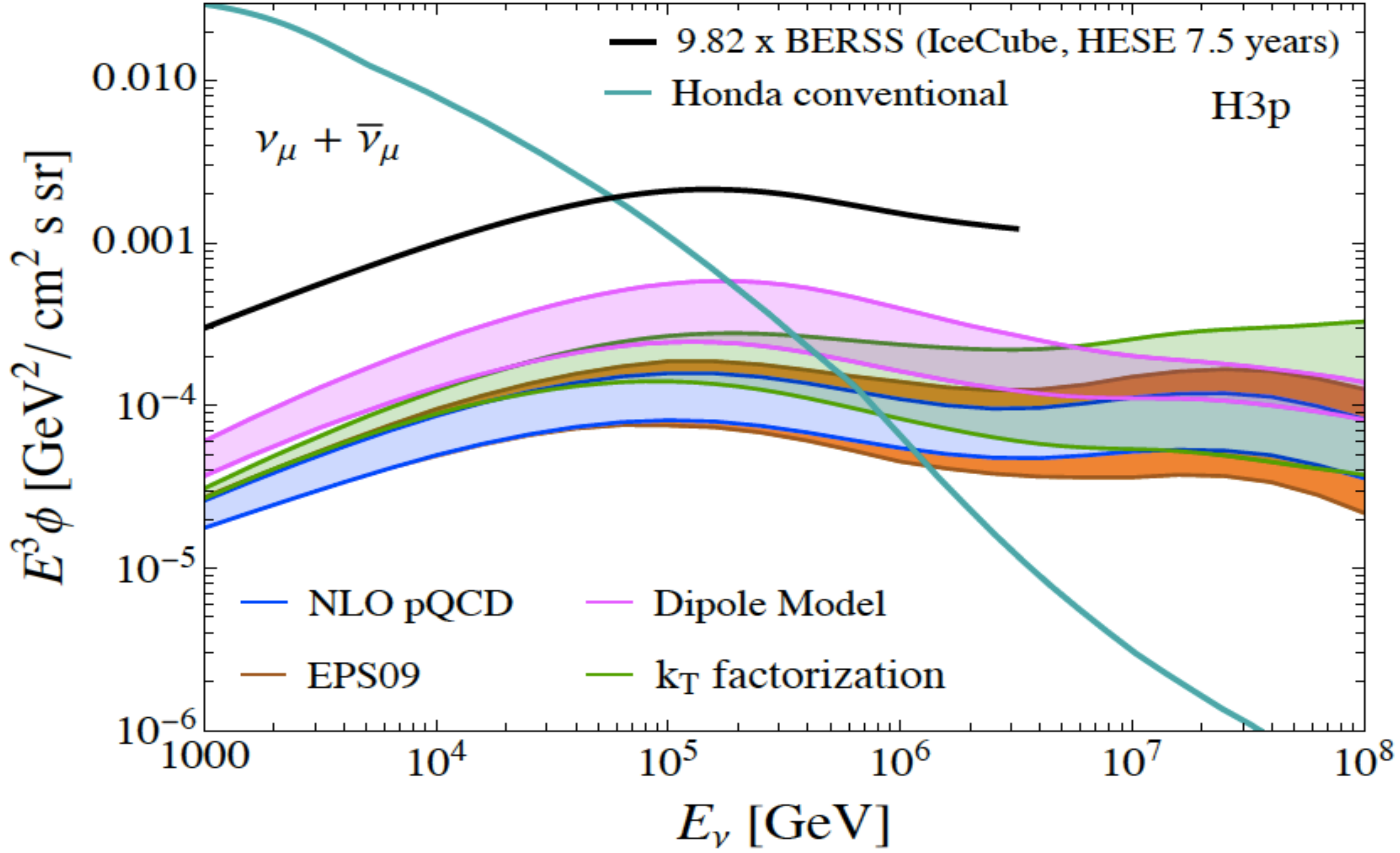
BPL=broken power law; H3a=cosmic ray flux



Prompt neutrinos are a background to astrophysical neutrinos

charm production and decay "prompt atmospheric neutrinos"

Prompt Neutrino Flux



A. Bhattacharya, R. Enberg, Y.S. Jeon, M.H. Reno, I. Sarcevic and A. Stasto, JHEP 11 (2016) 167

Main Goals:

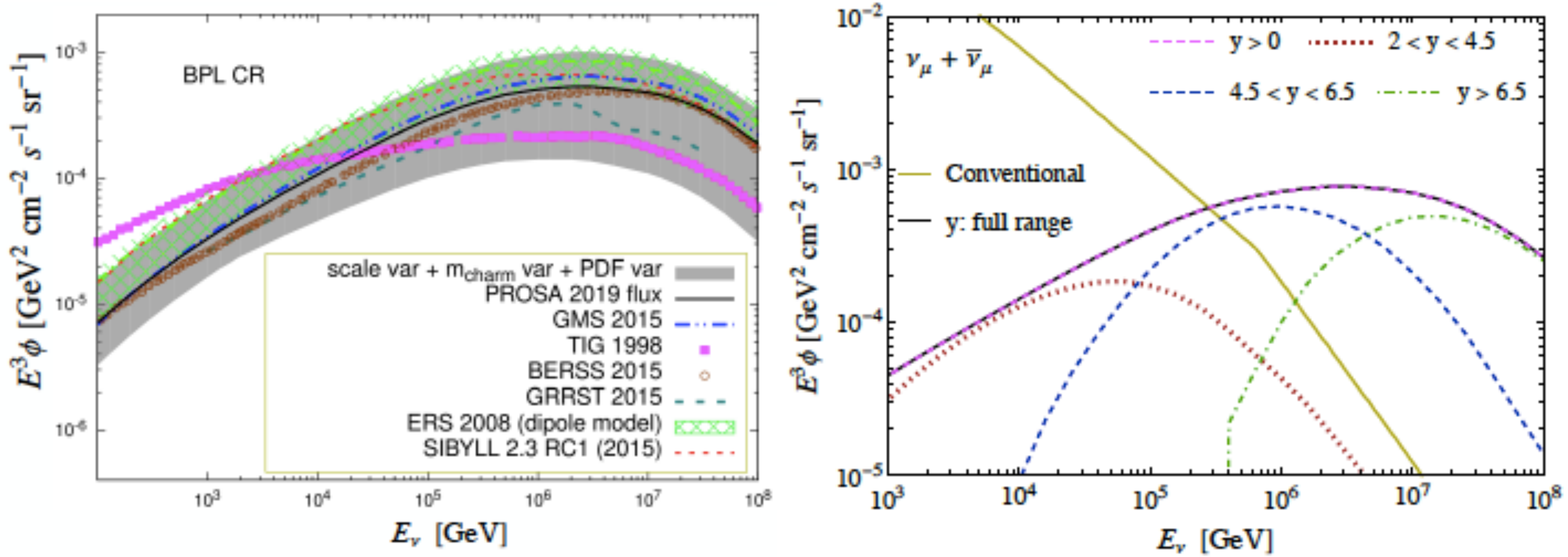
Explore neutrino production in the forward region (pursue FPF program)

Theory: Better understanding of perturbative QCD in the small x and small Q region, validity of factorization, improve fragmentation in hadronic collisions

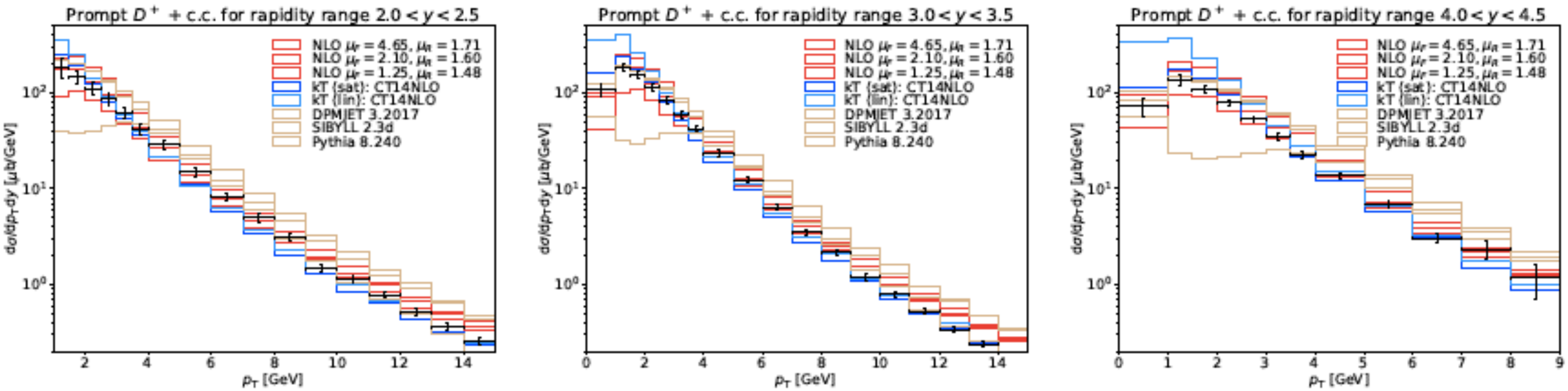
Pursue Forward Physics Facility Program at HL-LHC and Neutrinos telescopes such as IceCube-Gen2, km3Net.. Study correlations between these experiments, as well as multimessengers (gamma rays, cosmic rays, etc):

Backup Slides

Experiments The FPF is uniquely suited to exploit physics opportunities in the far-forward region, because it will house a diverse set of experiments, each optimized for particular physics goals. The envisioned experiments and their physics targets are shown in Fig. 2. FASER2, a magnetic spectrometer and tracker, will search for light and weakly-interacting states, including long-lived particles, new force carriers, axion-like particles, light neutralinos, and dark sector particles. FASERν2 and Advanced SND, proposed emulsion and electronic detectors, respectively, will detect $\sim 10^6$ neutrinos and anti-neutrinos at TeV energies, including $\sim 10^3$ tau neutrinos, the least well-understood of all known particles. FLArE, a proposed 10-tonne-scale noble liquid detector, will detect neutrinos and also search for light dark matter. And FORMOSA, a detector composed of scintillating bars, will provide world-leading sensitivity to millicharged particles and other very weakly-interacting particles across a large range of masses.



BPL CR
$E^3\phi$ [GeV^2 cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]
scale var + m_{charm} var + PDF var
PROSA 2019 flux
GMS 2015
TIG 1998
BERSS 2015
GRRST 2015
ERS 2008 (dipole model)
SIBYLL 2.3 RC1 (2015)
$\nu_\mu + \bar{\nu}_\mu$
y > 0
2 < y < 4.5
4.5 < y < 6.5
y > 6.5
Conventional
y: full range


Prompt D^+ + c.c. for rapidity range $2.0 < y < 2.5$
Prompt D^+ + c.c. for rapidity range $3.0 < y < 3.5$
Prompt D^+ + c.c. for rapidity range $4.0 < y < 4.5$
NLO $\mu_F = 4.65, \mu_R = 1.71$
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kT (sat): CT14NLO
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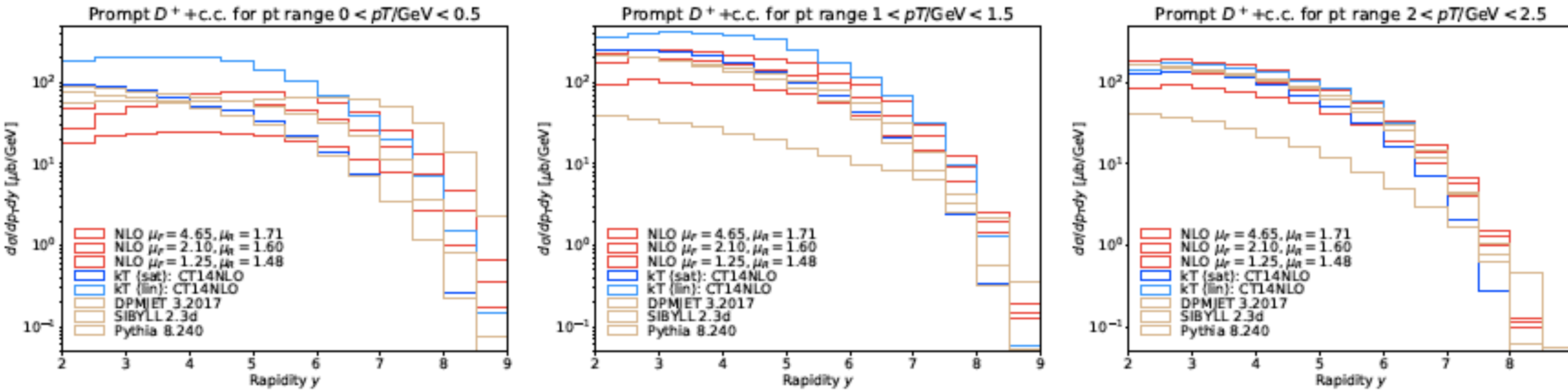
Pythia 8.240
$d\sigma/dp_T dy$ [μb/GeV]
p_T [GeV]



Prompt D^++c.c. for pt range $0 < pT/\mathrm{GeV} < 0.5$
Prompt D^++c.c. for pt range $1 < pT/\mathrm{GeV} < 1.5$
Prompt D^++c.c. for pt range $2 < pT/\mathrm{GeV} < 2.5$
$d\sigma/dp_T dy$ [μb/GeV]
Rapidity y
NLO $\mu_F = 4.65, \mu_R = 1.71$
NLO $\mu_F = 2.10, \mu_R = 1.60$
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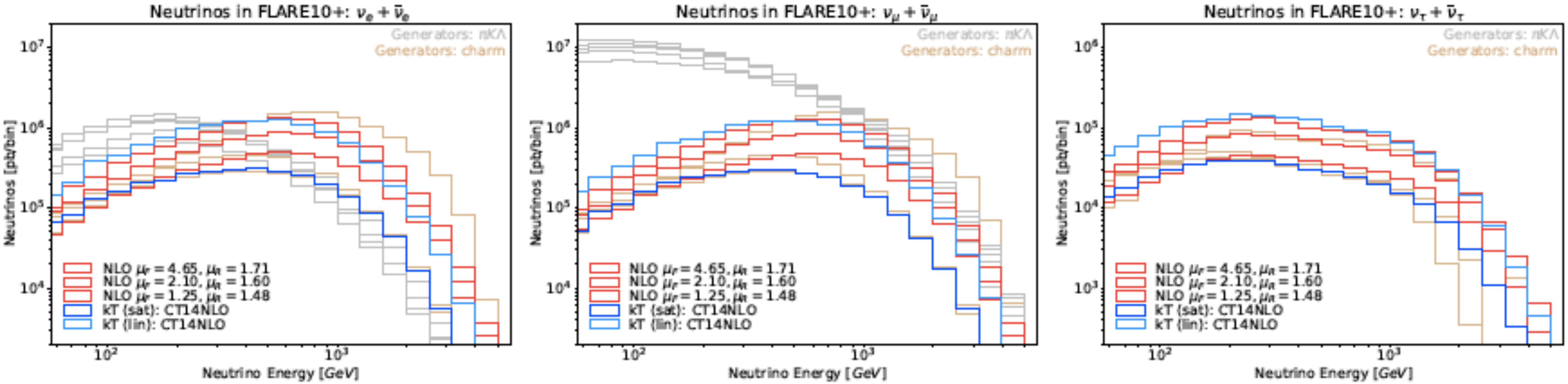
Neutrinos in FLARE10+: $\nu_e + \bar{\nu}_e$
Neutrinos in FLARE10+: $\nu_\mu + \bar{\nu}_\mu$
Neutrinos in FLARE10+: $\nu_\tau + \bar{\nu}_\tau$
Generators: $\pi K \Lambda$
Generators: charm
Neutrinos [pb/bin]
Neutrino Energy [GeV]
NLO $\mu_F = 4.65$, $\mu_R = 1.71$
NLO $\mu_F = 2.10$, $\mu_R = 1.60$
NLO $\mu_F = 1.25$, $\mu_R = 1.48$
kT (sat): CT14NLO
kT (lin): CT14NLO

Neutrino cross sections